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BROAD BAND SOUND FROM WIND TURBINE GENERATORS

H. H. Hubbard, K. P. Shepherd
and F. W. Grosveld

THE COLLEGE OF WILLIAM AND MARY
Virginia Associated Research Campus
Newport News, Virginia 23606

and

THE BIONETICS CORPORATION
Hampton, Virginia 23666

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Langley Research Center
Hampton, Virginia 23665

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INTRODUCTION

There is a growing interest in the concept of power generation by means of wind turbines. This has led to the development of large machines (of megawatt size) which may be located in single or in multiple units at many different places around the world. To date very few acoustic data are available for large wind turbines to use as a guide in their design and siting for acceptable environmental impact (Refs. 1-9).

The purpose of this paper is to characterize the problem of environmental noise for large wind turbines. The types of wind turbines that are of interest will be described briefly along with their sound characteristics. Sound sources will be identified and will be rank ordered for one machine for which systematic data are available.

TYPES OF WIND TURBINE GENERATORS

Currently operating wind turbine generators which cover a wide range of power ratings from kilowatts to megawatts can be categorized as vertical axis or horizontal axis machines as indicated in Figure 1. Vertical axis machines include the Darrieus and Gyromill types. They typically have 2-4 blades which rotate about a vertical axis and they are nondirectional with respect to the wind. The largest of this type are Darrieus machines having a rating of about 0.5 MW.

Horizontal axis machines are now operational in the 2 MW range. They have 2 or 3 blades, and operational speeds in the range 18-30 rpm. They are referred to as either upwind or downwind machines depending on the location of the rotor with respect to the supporting tower. They operate most efficiently when aligned with the wind vector.

A schematic illustration of a wind turbine sound spectrum is given in Figure 2. The discrete frequency components associated with both steady and fluctuating blade loads, are at multiples of the blade passage frequency and hence occur at very low frequencies. The broad band sound components on the other hand are associated with the turbulent inflow, the blade boundary layers, and wake turbulence. They arise from a number of different aerodynamic phenomena and consist of a wide range of frequencies from subaudible up into the normal range of hearing.

The presence of intense discrete frequency components has been limited to those horizontal axis configurations with downwind rotors and for which there is the possibility of strong rotor-tower wake interactions. Discrete frequency sounds also arise from the torque tube-blade interactions of vertical axis machines. Broadband sound, however, is of concern for all types of machines. The remainder of this paper will focus on the broadband components.

SOURCES OF BROAD BAND SOUND

There are a number of possible sources of broadband sound due to the interactions of rotating blades with the surrounding air. Some of these which could be important for the ranges of geometry and operating conditions of wind turbine generators are listed in Figure 3. Note that they are categorized as being associated with the turbulent inflow, the airfoil itself or the wakes.

Included are such phenomena as direct radiation from the aerodynamic wakes of the blades and the turbulent boundary layers on their surfaces, vortex shedding, separated flows due to localized stalling and the interactions of the aerodynamic flow with surface roughness, protuberances, cavities and slots. As will be illustrated subsequently, measurements on a large horizontal axis upwind machine suggested that its two main noise sources are inflow turbulence and turbulent boundary layer interactions with the blade trailing edges. None of the other sources seemed to be important.

ACOUSTIC MEASUREMENTS ON MOD-2 MACHINE

Test Site

The opportunity was taken to make a systematic series of sound measurements on the DOE-NASA-BPA MOD-2 machine shown in the inset photograph of Figure 4. It is a two blade, horizontal axis, upwind machine which has a 300 foot diameter rotor and an rpm of 18. It is located in the Goodnoe Hills region on the north rim of the Columbia River Gorge in the State of Washington. Examples of acoustic data from Ref. 1 are shown in Figures 5, 6 and 7.

Example Sound Spectra

Measurements in both the near and far acoustic fields indicated characteristic spectrum shapes such as those in the example plot of Figure 5. Note that two broadband sound peaks are present and these result from different aerodynamic flow phenomena on the blades, as indicated by the airfoil sketch.

Available evidence suggests that the low frequency peak is associated with inflow turbulence. Random velocity fluctuations cause effective angle of attack changes which in turn result in unsteady lift and drag loads and associated sound radiation. These sound components are measurable and will propagate with very little atmospheric attenuation, but are not readily observable above the background noise.

On the other hand, the higher frequency peak is believed to result from the interactions of the turbulent boundary layers on the airfoil surfaces with the airfoil trailing edge. These sound components seem to dominate the spectra near the machine, and are in a frequency range where the ear is sensitive and the background noise level is low. Detection distances at the operational site where the background A-scale noise level was about 30 dB were about 1400 m (4600 ft) upwind and in excess of 2100 m (6900 ft) downwind.

Effects of Distance

Figure 6 contains a plot of measured sound pressure levels as a function of distance for comparison with predictions. For information an example instantaneous pressure time history for one of the measuring points is shown in the inset at the bottom of the figure. It was assumed for the predictions that the observer was at ground level in front of the machine and that the sound source could be represented by a concentrated dipole at hub height. Two results can be seen. The predicted and measured values seem to be in excellent agreement except for the close-in stations. This good agreement may be fortuitous because of the possible wind noise contamination of some measured data. The apparently good agreement for the predicted and measured fall off rates with increasing distance suggests that the machine can be represented adequately as a concentrated dipole source for far field sound prediction purposes.

Far Field Contours

Based on the data of Figure 6 plus other measurements and observations the polar diagram plots of Figure 7 have been constructed. Shown on Figure 7 are estimated A-level contour lines for 65, 55, 45 and 35 dB values. Shown also is the detection limit distance of about 1400 m for the southwest quadrant, for which the A-level background noise was about 30 dB. In the downwind direction, the sound was clearly audible at a distance of about 2100 m, thus confirming the existence of an elongation of the radiation pattern in the downwind direction. This elongation is believed due to the refraction effects of the wind rather than to any preferred directional properties of the source.

It was generally observed that the upwind (west direction) propagated sound signals were relatively steady in amplitude. On the other hand in both the south direction (crosswind) and the east direction (downwind) the sound signal had a perceptible amplitude modulation at the blade passage frequency. It has thus been suggested that at the larger distances (particularly downwind), the sound may be detectable from only the topmost portion of the rotor disk.

CONCLUDING REMARKS

Measurements on a large upwind configuration wind turbine suggest that the main source of sound is the rotor rather than the gears, shafts and electrical generation equipment. Broadband components dominate the sound spectrum and they are noted to arise from inflow turbulence and from turbulent boundary layer-trailing edge interactions. Sound is radiated about equally in all directions but the refraction effects of the wind produce an elongated contour pattern in the downwind direction.

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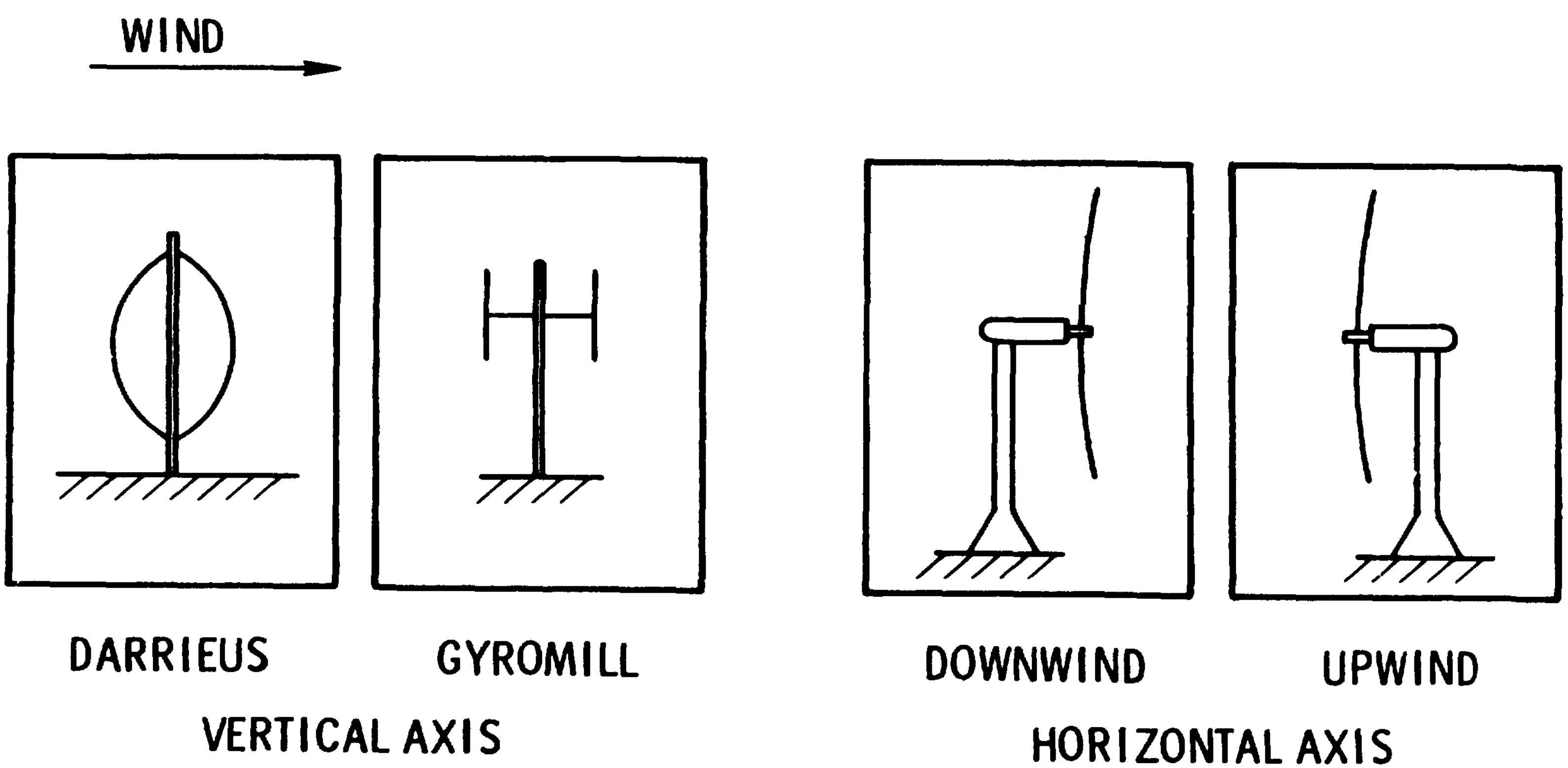

Figure 1.- Types of large wind turbine generators.

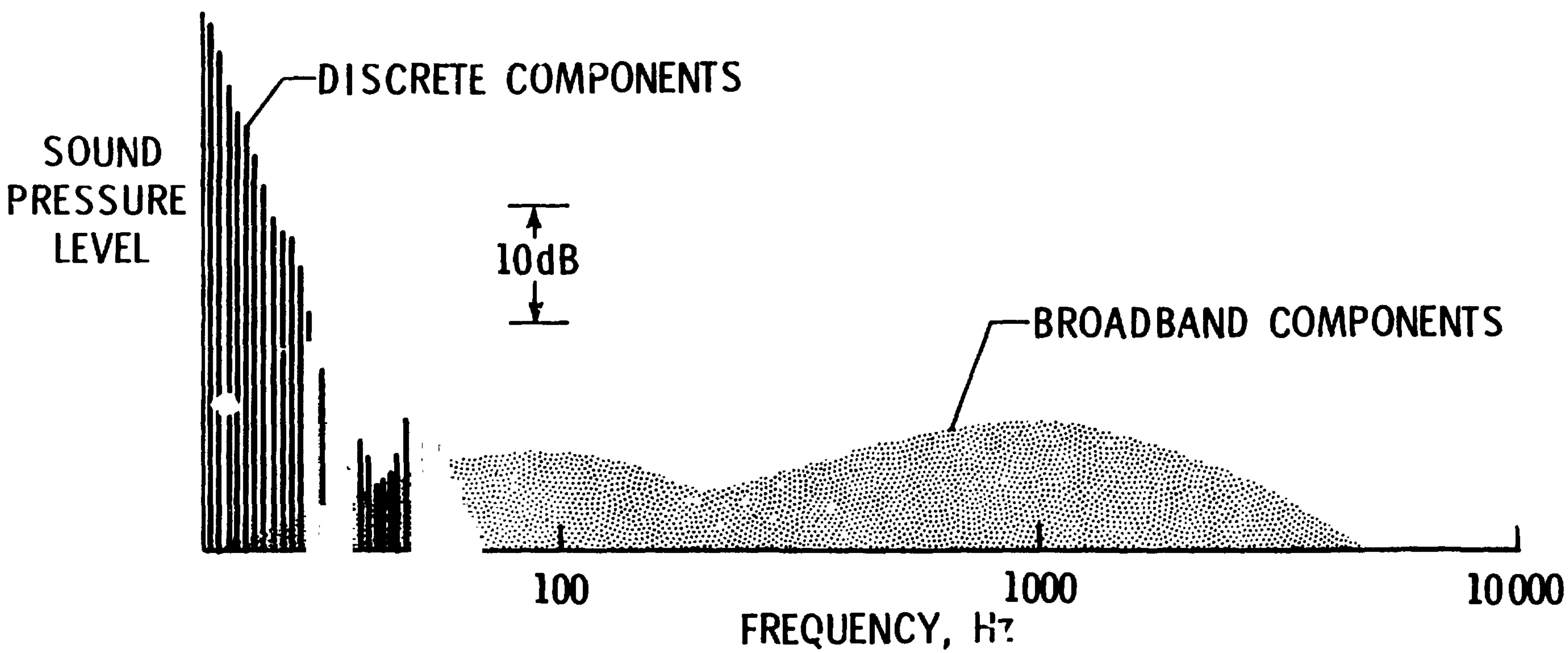

Figure 2.- Schematic diagram of sound spectrum from large wind turbine generator.

- INFLOW TURBULENCE
- SEPARATED FLOWS
- BOUNDARY LAYER RADIATION
- SURFACE ROUGHNESS
- PROTUBERANCES
- CAVITIES
- SLOTS
- TIP VORTICES
- TRAILING EDGE WAKES
- WAKE RADIATION
- TURBULENT BOUNDARY LAYER-TRAILING EDGE INTERACTIONS

Figure 3.- Possible aerodynamic broadband sound sources on rotating blades

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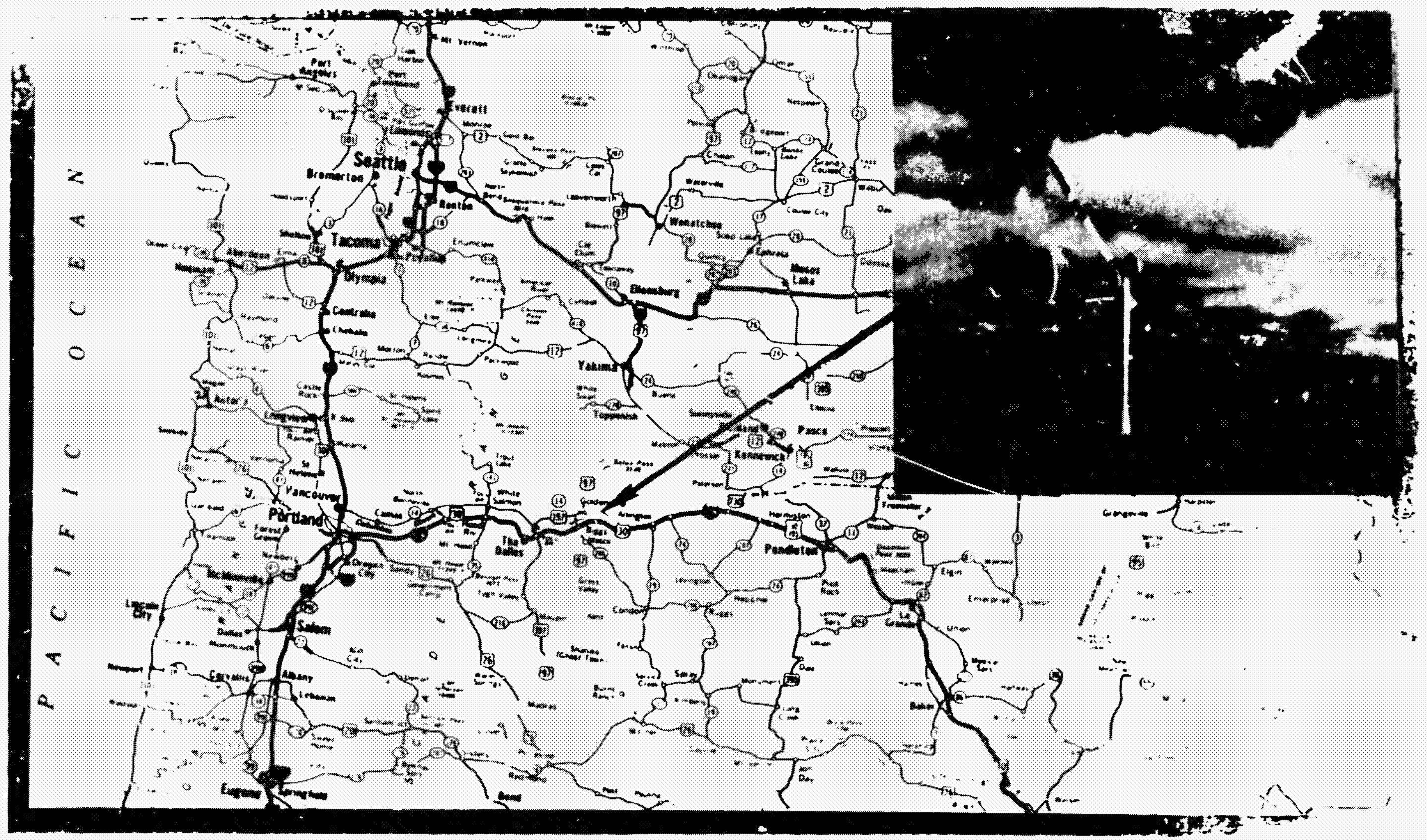

Figure 4.- Test site for MOD-2 wind turbine generator. (REF 1)

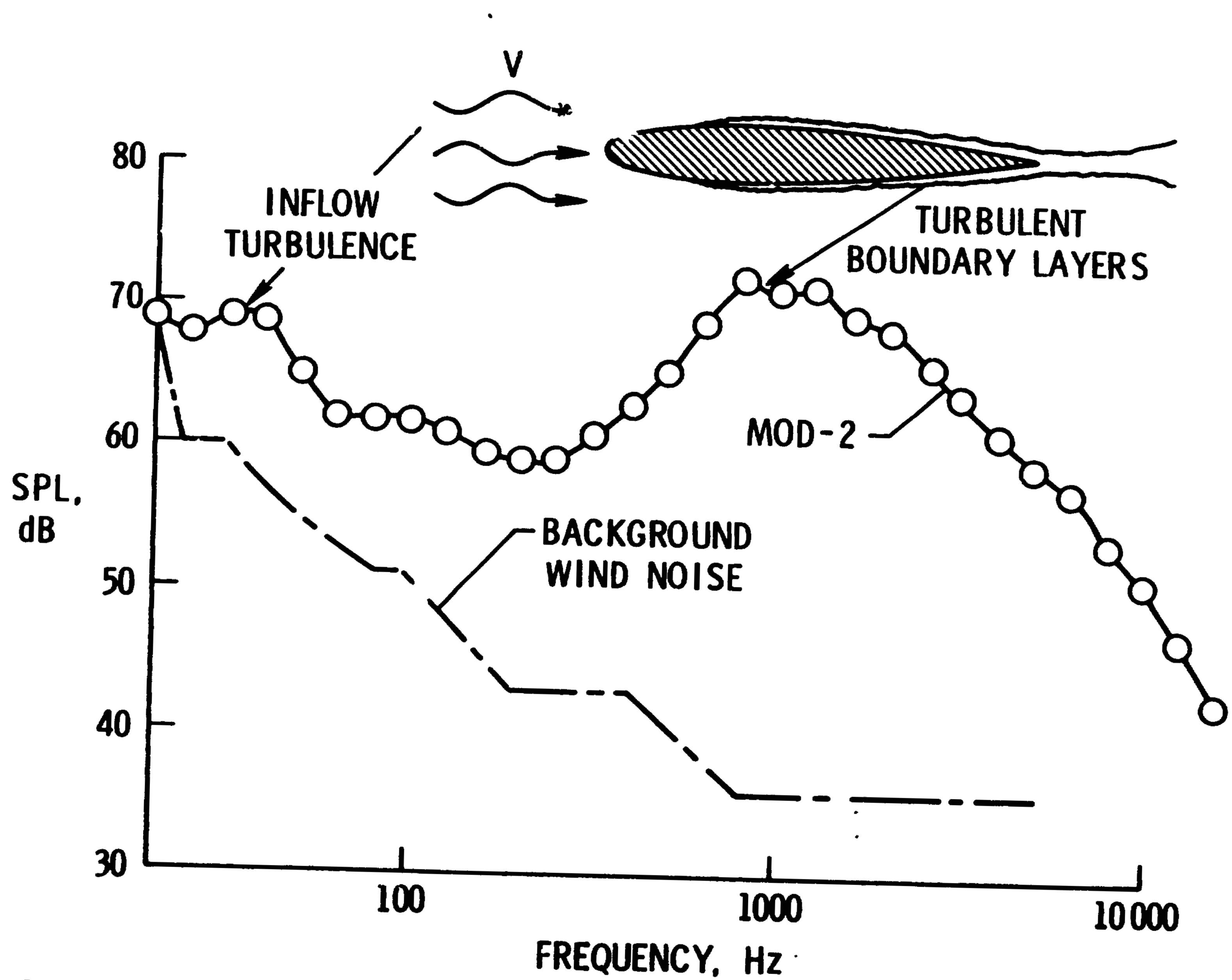

Figure 5.- Example near field one third octave band spectrum of broadband sound for MOD-2 wind turbine generator. (REF 1)

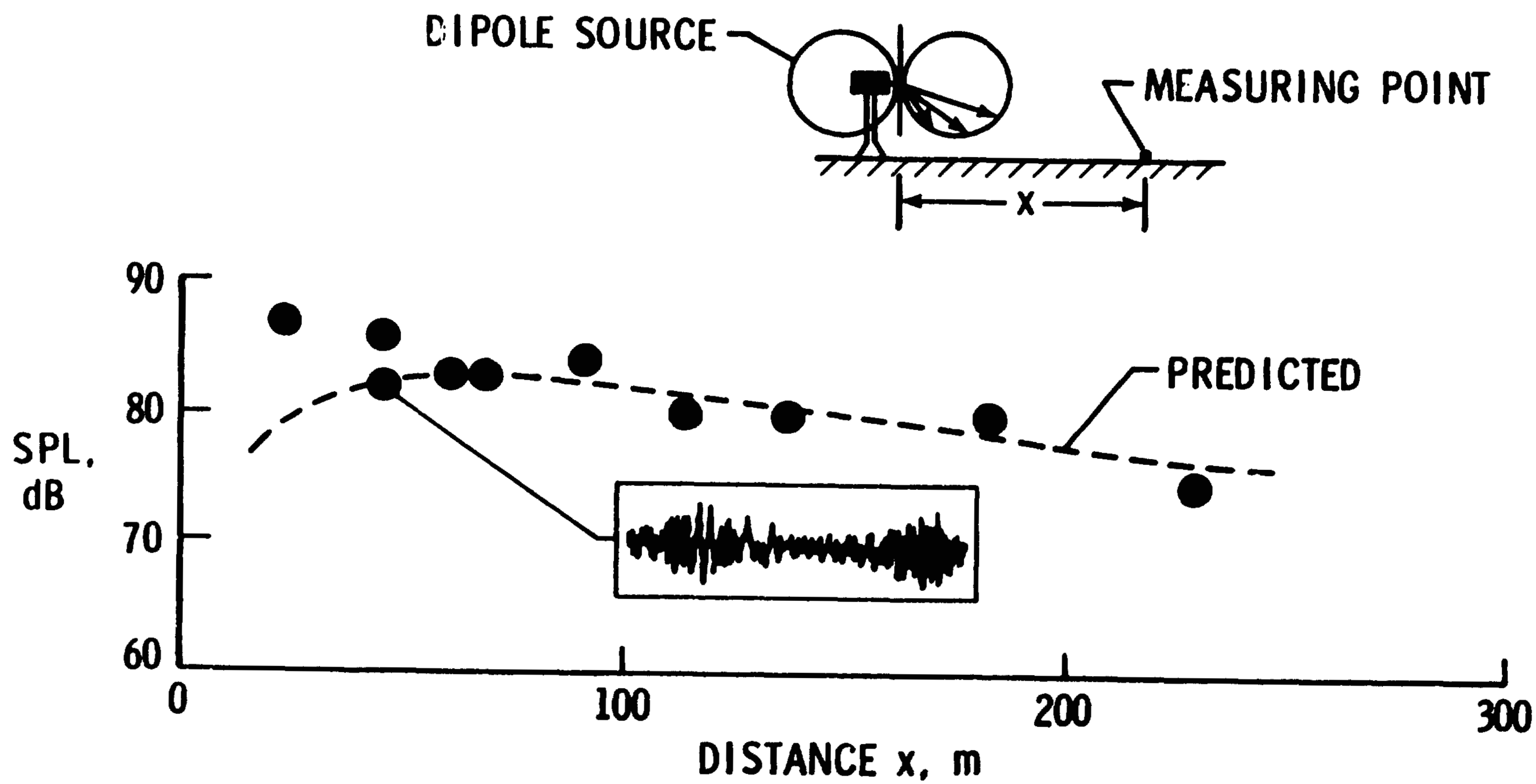

Figure 6.- Measured and predicted effects of distance on broadband sound levels for MOD-2 wind turbine generator. (REF 1)

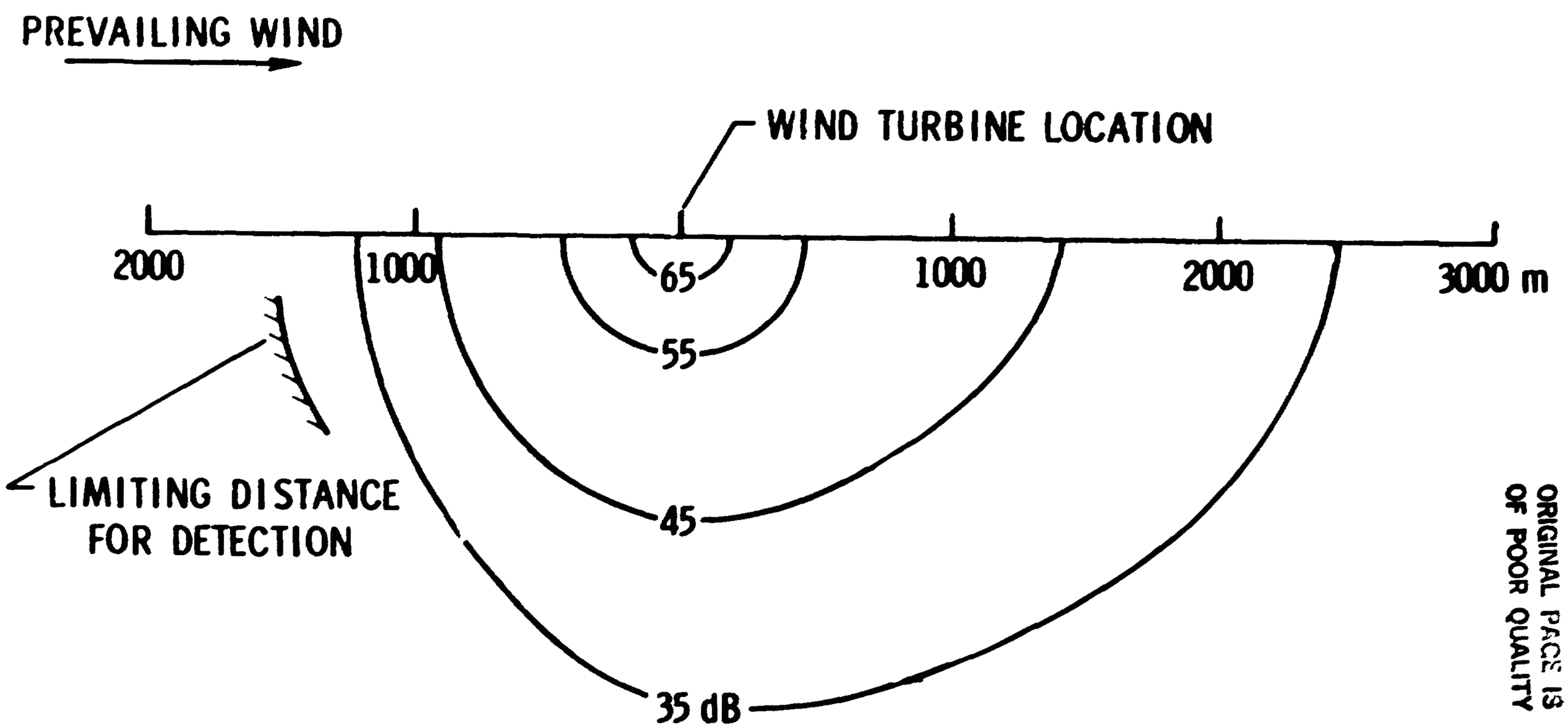

Figure 7.- A-level sound contours for MOD-2 wind turbine generator. (REF 1)